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SHALE FOUNDATIONS FOR EARTH DAMS

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WATERWAYS DIVISION

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SHALE FOUNDATIONS FOR EARTH DAMS

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This paper deals with only one of many types of foundation materials—namely—shale. One of the reasons for selecting shale foundations as an appropriate subject for discussion is that they constitute almost 60 per cent of all sedimentary rocks and are encountered frequently as the foundation material upon which an earth dam or its appurtenant structures must be designed and built. As an example, of 17 sizeable dams already constructed within the State of Texas (each with storage capacity of over 200,000 acre feet) 13 of them involve shale foundations in some phase of their design and construction. In addition, 9 of the dams in Texas, now under construction by the Corps of Engineers, involve shale foundations. It should be added, however, that none of these 9 dams is founded entirely on shale, although the latter was an important consideration in the design and construction of each one of them.

Final selection of a dam site normally is based on the comparison of the engineering feasibility and project cost of various potential sites. Such comparison can be made only from a careful analysis of the several important factors or characteristics of the site. Of these factors, the character of the foundation is especially important, for its inherent characteristics, which cannot be altered materially, influence both the design and project cost.

The foundation must be considered an integral part of the dam and the suitability of the foundation is a requisite to a structurally sound dam. The foundation of a dam serves two primary purposes; first, to provide stable support for the structure under all conditions of loading, and second, to provide necessary resistance to the passage of water so that the purpose of the structure may be fully realized. Unless the foundation can meet these two requirements, total or partial failure of the structure may result.

A poor or unprotected foundation may result in the failure of an earth dam from one or more of the following causes:

*1) Plastic flow, as characterized by excessive movement, or squeezing out, of the foundation material without failure along any well defined shear plane. The reported cause of failure of Marshal Creek Dam in Kansas was plastic flow. The failure of the dam resulted from a plastic movement of foundation materials deficient in shearing strength. The plastic movement was caused by overloading of the foundation by a combination of height of dam and steepness of slope.

2) Shear, the result of loading a foundation beyond its shear strength as evidenced at Fort Peck Dam in Montana. The Board of Consultants called to investigate the slide concluded that the slide "was due to the fact that the shearing resistance of the weathered shale and bentonite seams in the foundation was insufficient to withstand the shearing force to which the foundation was subjected."

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* Examples cited in items 1 through 5 are from Engineering for Dams, Vol. III, Creager, Justin and Hinds.

3) Piping, the result of water flowing through the foundation with sufficient velocity, to wear away the foundation leaving the embankment unsupported. Failures or partial failures have been attributed to this cause, with the Greenlick, Scottsdale Dam, in Pennsylvania, as an example.

4) Scour, or erosion of the foundation may result from the flow of surface water, leaving the embankment or spillway structure partially unsupported. At Balsam Dam in New Hampshire, the spillway discharge eroded the downstream toe, causing sloughing, and at Waco Dam in Texas, the spillway discharge eroded the unprotected Eagle Ford shale so that the structure was dangerously undermined.

5) Sliding may result if the frictional resistance of the foundation strata, or in the zone between the foundation and the base of the dam is exceeded; the dam may slide over the foundation, or the foundation may slide over its own planes of stratification.

6) Uplift, under a relatively light structure such as spillway weir, walls or apron, may result in failure if the foundation includes permeable strata.

These possible causes of failure of earth dams are recited to illustrate specifically some of the factors which must be considered in determining suitability of a foundation for an earth dam. Long experience with shales does not relieve the design engineer from careful and detailed analysis of the foundation upon which he must build. The term "shale" by no means signifies one homogeneous substance. Shales represent the by-product of millions of years of weathering and breaking down of preexisting rocks and are as diverse in their behavior and characteristics as the rocks from which they originated.

Shales are solidified clays, muds, or silts that possess a thinly stratified or laminated structure. They are commonly called "clay rock" because of certain resemblances to clay, but there are many physical distinctions between clays and shales, due to the much greater degree of compaction or solidification of the latter. Shales for example, when confined, do not ordinarily become plastic when saturated with water. On the other hand, many shales break down rapidly into plastic clays when subjected to alternate drying and wetting. The distinct uniform stratification or bedding of the fine particles composing shale reduces its frictional resistance and precaution must be taken to prevent sliding of the dam over the foundation or sliding of one layer of the foundation material on another.

Hydrous aluminum silicates, quartz, iron in various forms, calcium carbonate and organic matter are the most common constituents of shale. As the amount of quartz increases and the grain sizes increase, shales grade into sandy shales and sandstones. They grade into calcareous shales and limestones as the calcium carbonate content increases. Some shales grade to coals when carbonaceous, or to oil shale when bituminous--others are ferruginous when high in iron content.

The non-calcareous shales are, as a rule, resistant to purely chemical weathering. However, many of them, when exposed, weather rapidly as a result of physical processes and revert to the soils from which they were originally formed.

Solidification of shales may be the result of either compaction or cementation. Compaction shales are the result of compressive forces exerted by the superincumbent materials acting over long periods of geologic time and cemented shales are largely the result of cementation of clays, muds, and silts by calcareous, siliceous, or ferruginous materials. Compaction shales are weaker foundation materials than cemented shales and they disintegrate rapidly when subjected to alternate drying and wetting. While fresh shales are

fairly resistant to erosion from flowing water, the rapid and deep disintegration of most shales when exposed to weathering requires that they be protected against scour.

Unweathered and undisturbed shale is a material of low permeability; consequently, it rarely introduces problems of underseepage. However, when shale is interbedded with other strata, particularly those of a sandy nature, under-seepage may become a problem to be met by grouting, core-trenching, or relief wells, but experience in the Fort Worth District has disclosed no serious difficulties of this nature. Massive shale beds may pass some water through joints and fractures within the beds. This condition, however, ordinarily is not serious in the unweathered and undisturbed strata. Thus, for the immediate purpose of this paper, under-seepage in shale foundations will not be treated.

For the design and construction of an earth dam on a shale foundation, it is important that adequate information be obtained on the geology and physical characteristics of the formations involved. Toward this end the engineer should seek the advice of a competent engineering geologist. A comprehensive exploratory program involving core borings, test pits, trenches, water pressure tests, and sometimes large diameter holes to permit direct inspection of the foundation in place, should be resorted to in order to develop the subsurface conditions and physical characteristics of the foundation materials adequately.

Various types of borings should be made in order to determine the nature of the foundation. For the more important phases of the investigation, particularly with shale foundations, 6-inch undisturbed samples should be taken with the Denison-type sampler or with the 6-inch core barrel. These samples should be tested for amount and rate of consolidation under various superimposed loads. Direct shear tests and unconfined compression tests should be made to determine the strength characteristics of the shale in its undisturbed state. Direct shear tests, made under varying normal loads, yield the two principal design factors. These are c, which defines cohesion in terms of tons per square foot, and ϕ, the angle of internal friction. Frictional resistance to shearing stress is a variable, and is equal to the superimposed normal load, in tons per square foot, multiplied by $\tan\phi$. Although direct shear tests provide a greater amount of data than unconfined compression tests, the unconfined compression test finds much favor because of its relative simplicity and rapidity. Thus, a large number of unconfined compressions may be made in lieu of a relatively few shear tests.

Often shale foundations may be satisfactory in some respects yet unsatisfactory in others. They may be impermeable yet lack required strength as foundation for certain structures. They may have ample strength yet because of dip of the beds may be subject to sliding, or, have great strength yet contain permeable seams of sand. When shale beds are found to be badly jointed, seamy or fractured by structural deformation, cut-off walls and grouting may be required to strengthen the foundation or decrease leakage. Such precautionary measures were required at Mt. Morris Dam in New York, where vertical mud seams were cut-off by grouting and cut-off walls. One of the biggest problems in shale foundations is the construction difficulties involved. In massive, unfractured shale beds this is due almost wholly to the fact that in physical characteristics weathered shale is entirely different from fresh shale. For example, foundation cuts cannot be made immediately to neat line. Common practice requires excavation to within 2 to 4 feet of final neat line or grade with the final precise cut made immediately before forming or backfilling. It is essential to anticipate such construction difficulties and to provide for them in design, plans and specifications.

Various types of shales have been encountered to some extent at several projects involving earth dams in the Fort Worth District. The following discussion points out problems encountered in utilizing these shales as foundation materials and construction practices followed in treating them:

At Hords Creek Dam the embankment section, in the floodplain area, is founded on alluvial deposits which overlie shale and limestone of the Belle Plains formation of Permian age. These strata also occur both in the right and left abutments. The shales are hard, calcareous, laminated, impervious, and are interbedded with thin bands of limestone. Unconfined compression test results on these shales ranged from 10.5 to 24.6 tons per square foot. Weathering has penetrated only 1 to 2 feet into these shale beds, where protected by alluvial materials, and from 5 to 10 feet into these materials where exposed at the surface or are overlain by a thin residual mantle. These shales served an important feature of the dam foundation. Investigations revealed the alluvium and weathered portions of the shale and limestone beds to be pervious; therefore, a core trench was dug through these materials into unweathered, impervious shale and was backfilled with impervious material to serve as a positive cut-off of seepage under or around the ends of the dam. Similar measures to prevent dangerous underseepage or piping through embankment foundations by tying the impervious core of the dam to impervious foundation shales, through the use of a cut-off trench, were adopted at the Benbrook and Grapevine Dams and are to be a foundation feature of the Bolton Dam. Another feature of the Hords Creek Dam is the emergency spillway cut into a low saddle on the right abutment. The base of the spillway cut is in shale strata of the Clyde formation of Permian age. This shale is moderately hard, sandy, and lightly cemented with calcareous materials. It extends 10 feet below the spillway floor to a massive limestone bed. Minor limestone bands occur in the 10 foot shale section. No protective concrete slab or weir section was provided over the spillway foundation. Examination of this shale at surface outcrops and in core samples indicated that weathering processes would be relatively slow. Hydraulic studies indicated that the expected frequency of any discharge through the spillway would be in the order of magnitude of about once in 50 years. Therefore, since the foundation shale does not weather rapidly, is fairly resistant to erosion, and the underlying massive limestone would block any deep erosion in the spillway, it was decided to omit the costly concrete work usually required for such spillways.

At Benbrook Dam the rolled earth fill is founded on alluvial and residual deposits. Here, as at Hords Creek Dam, it was necessary to cut a core trench through the pervious alluvial, residual and weathered rock strata to unweathered shale or argillaceous limestone to eliminate dangerous seepage under the dam. The core trench is cut into hard, calcareous shales and argillaceous limestones of the Goodland, Kiemichi. and Duck Creek formations of Cretaceous age. Weathering of these materials, as evidenced by core boring and trenching operations, increases from 2 to 3 feet beneath the floodplain area where they are protected by thick alluvial deposits, to 5 to 8 feet on the abutment slopes and to as much as 20 feet below the rock surface on top of the abutment where no protective alluvial or residual cover is in existence. Unconfined compression tests on unweathered foundation shales at Benbrook Dam ranged from 15 to 29 tons per square foot.

The outlet works foundation at Benbrook Dam was cut into calcareous shale and highly argillaceous limestone strata of the Goodland formation. These foundation materials were found to be more resistant to erosion than most shales, but as an added precautionary measure, all shale and argillaceous

limestone faces were sprayed with a heavy asphaltic coating as soon as cuts had been made to final grade to prevent weathering or spalling of the foundation rocks. This method proved to be very effective as a protective measure for the foundation material encountered at Benbrook Dam.

Foundation examinations during excavation operations at Benbrook Dam revealed the presence of small horizontal seams along the contact planes between alternating shale and limestone strata in the steep right abutment. The abutment had already been cleaned off to sound unweathered rock; therefore, rather than remove sound foundation materials from the abutment, a series of grout holes were drilled normal to the steep abutment slope in order that all possible horizontal shale-limestone contacts would be intercepted. These holes were then pressure tested and grouted, effectively sealing potential zones of leakage around the end of the dam.

At Grapevine Dam the outlet works, located in the floodplain at the toe of the left abutment, and the spillway, located in a low saddle on the left abutment, are founded on arenaceous shale and argillaceous sandstone strata of the Woodbine formation of Cretaceous age. The outlet works consist of a 142' high intake structure, a 13-foot diameter conduit 485 feet long, and a stilling basin. The foundation materials at the outlet works are principally compact, impervious, arenaceous shales interbedded with argillaceous or shaly, medium to fine-grained sandstones. Unconfined compression tests on the arenaceous shales showed results ranging from 2.3 to 20 tons per square foot and strengths of 20 to 28 tons per square foot on the shaly sandstones.

Examination of the shales and sandstones at the surface exposures and cores from exploratory borings indicated that surfaces exposed during construction would be subject to deleterious weathering unless adequately protected until construction materials were placed against them. Therefore, during construction in no case was a shale surface, against which materials were to be placed, allowed to remain uncoated or uncovered for more than 4 hours after exposure. Usually excavations were made to within 1 foot of final grade—this 1 foot of undisturbed material acting as protective cover. After removal of the covering of undisturbed material the horizontal or approximately horizontal foundation surfaces were covered with a 3-inch protective concrete slab—the vertical or nearly vertical foundation surfaces were protected by an application of asphalt sealer.

Similar treatment was applied to the foundation shales and argillaceous sandstones in the spillway area, except that in the spillway apron excavation a 1 foot protective cover of undisturbed material was left in place until concreting operations were begun. This protective covering was then removed and the entire apron slab poured on exposed foundation materials, but in no case was exposure allowed in excess of 4 hours. Experience proved these measures to be entirely satisfactory for protection of the foundation materials. To overcome possible excessive hydrostatic uplift pressures beneath the floor slab of the stilling basin and of the outlet works spillway apron, 1 inch and 1-1/4 inch anchor bars were grouted 10 feet into the shale and sandstone foundations. In addition, 4-inch drain holes were provided in the floor slab of the outlet works stilling basin to help relieve possible hydrostatic uplift pressures.

There is no single dam in the Fort Worth District in which all elements of the structure are founded directly upon shale, but perhaps the best example of problems of a shale foundation is Lavon Dam on the East Fork of the Trinity River a few miles north of Dallas. Here the gated spillway is founded on a shale-like material of the Taylor group of Upper Cretaceous age. Technically the Taylor is a marl or calcareous clay rather than a true shale.

However, due to their shale-like characteristics, these marls are referred to and treated as shales in engineering practice. This material is moderately hard, compact, massive, dark gray to black, and calcareous. The embankment itself is constructed on alluvial deposits of 40 to 50 feet in thickness. This alluvium is chiefly silty clay derived from breakdown of the Taylor shales in the reservoir area. In the abutment areas, the shales have weathered to form a 20 to 30 foot blanket of residual clay and have weathered as much as 20 feet below the residuum. In the embankment area, unconfined compressive strengths on the weathered shale ranged from 0.7 to 9 tons per square foot, and on unweathered shale from 17 to 30 tons per square foot. In the spillway area, weathered shales tested 1.4 to 12.9 tons per square foot and unweathered shales tested 14 to 28 tons per square foot.

Embankment design in this case was governed by the strength of the clay residuum. Although borrow material for the embankment had sufficient cohesion and frictional resistance to produce a safe condition with relatively steep slopes, the weakness of the clay foundation necessitated flattening of the slopes, which in the design finally adopted, vary from 1 on 2.75 to 1 on 6 on the downstream slope and from 1 on 2.85 to 1 on 5 on the upstream toe. Also, a shale fill was placed on a 1 on 8 slope along most of the upstream toe as an additional counter-balance to sliding.

The spillway at Lavon Dam was excavated and constructed under two contracts. The first contract consisted of all excavation within 2 feet of final grade in the approach channel, weir, and stilling basin areas and spillway notch. The approach channel and weir excavation resulted in a relatively flat surface; whereas the upstream half of the stilling basin area was left on a 1 on 3 slope. The 30-foot walls of the spillway notch were left almost vertical at the start of the excavation, but excessive disintegration and spalling of the shale made it necessary to lay back these cuts on a gentler slope. Several months elapsed between completion of the first excavation contract and final dressing of the spillway cut to grade. Examinations of all exposed shale surfaces in the spillway cut showed that leaving 2 feet of undisturbed shales as protective covering on the near vertical cuts was inadequate and that sloughing as much as 5 to 7 feet behind the original cut had taken place. The 2 feet of undisturbed protective shales in the spillway discharge channel excavation and on the horizontal approach channel were entirely adequate as protective measures. It was noted that where water had ponded, in flat surfaces or shallow depressions after the original excavation, only 6 inches of weathered material had to be removed to expose fresh shale surfaces. Attempts were made to control the disintegration of shales on the high, steep cuts by spraying with asphaltic compounds without marked success. However, spraying of shales with asphalt on low vertical cuts proved successful.

It was originally planned to form the concrete training walls of the stilling basin directly against the shale and secure the 3 feet of concrete by anchor grouting into the shale. After the original cuts were made, the shale disintegrated so rapidly on exposure, and appeared so generally weak, that the plans were changed and a cantilever retaining wall, varying from 15 inches in breadth at the top to 6 feet in breadth at the bottom was substituted. As the shale along the spillway wall disintegrates upon weathering into very minute particles, drains behind these walls were designed so as to reduce the danger of clogging by infiltrating fines. This was accomplished by graded filter materials in which transition in particle size provided increase in permeability from the shale mass towards the drain, plus stability against infiltration of the finer sizes into the coarser.

A spillway stilling basin concrete floor slab, 3 feet in thickness, the downstream half of which lies horizontal and the upstream half of which lies on a 1 on 3 slope, is tied to the shale foundation by means of anchor bars grouted into the shale. These anchors were considered necessary to guard against the possibility of excessive hydrostatic uplift by water entering between the bottom of the concrete and the top of the foundation. The anchors are 1-1/4" deformed steel reinforcing bars and are set on 7-foot centers normal to the dam axis and on 8-foot centers parallel with the dam axis. When the shale foundation was cut to final grade, a 3-inch slab of concrete was immediately placed to protect the shale against weathering. Holes were drilled through this 3-inch slab and into the foundation to a depth of 10 feet and the anchor bars grouted into these holes.

In conclusion it seems appropriate to quote a paragraph from the chapter on "Geology in Dam Construction" of the Berkey Volume of the Geological Society of America by E. B. Burwell, Jr., and B. C. Moneymaker:

"No class of foundation rocks varies more widely than shales. Unfortunately, the term shale, in its loose usage, has come to signify to many a foundation rock of poor quality and unsavory reputation. Such categorical condemnation has led to many false appraisals of dam sites, and much ill advice as to the critical problems of shale. Some shales have strengths comparable to those of good concrete and, being rocks of low permeability, provide excellent sites for dams. Others, having attained a degree of solidification but slightly greater than those of compact soils, exhibit properties more like soil than rock. They, therefore, introduce some of the most troublesome problems of design and construction—problems of consolidation under load; of rebound following unloading; of rapid deterioration under alternate drying and wetting; of slides from oversteepened valley walls and construction slopes; and of shear and sliding failure. Between these two extremes are many kinds and types of shale whose problems vary widely according to their degree of solidification, their structural conditions and their topographic setting."

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c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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